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Solar Photovoltaics for Irrigation Water Pumping

by Urs Rentsch

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Urs Rentsch

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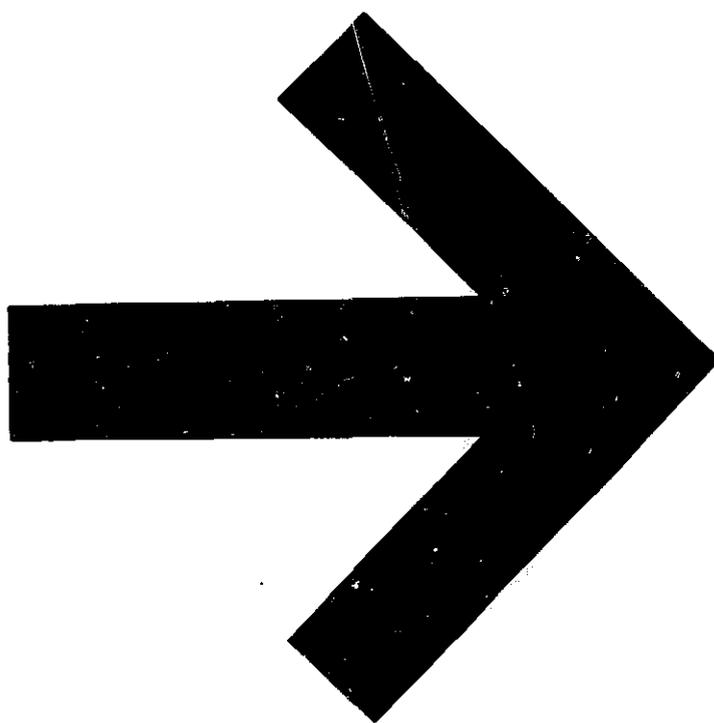
SOLAR PHOTOVOLTAICS FOR IRRIGATION WATER PUMPING

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SOLAR PHOTOVOLTAICS FOR IRRIGATION WATER PUMPING

a) Background information

The economic development of rural communities in most developing countries is heavily dependent upon increased agricultural productivity. An alarming fact is that the feeding of the worlds population will get more and more difficult in the near future, as population is rapidly growing and the fertility of the soil is decreasing in many areas.

Irrigation is widely recognized as a feasible yield-increasing technology which could play a key role in improving food production. In areas, where irrigation with gravity-fed water through controlling the flow of rivers and suitable canal distribution systems is not possible, the need for a cheap, readily available energy source is obvious.

Since conventional mechanized irrigation through engine-driven pumps is getting more and more expensive with climbing fuel prices, the use of solar radiation for water pumping is becoming interesting.

There are several technical options to convert solar radiation to electricity or mechanical energy. The most advanced option and probably the most feasible one for the immediate future is the use of solar (or photovoltaic) cells.

Although scientifically complex, photovoltaic cells are conceptually quite simple. They convert the sunlight directly to electricity. By joining large numbers of these cells together (modules and arrays), significant amounts of power can be generated whenever the sun shines.

The main advantage of the photovoltaic generator is its reliability. Its life time is expected to reach 20 years. Other advantages are, that the electrical energy can be generated right at the site of use and that it has very low running costs, i.e. low maintenance requirements and no fuel costs.

The major barrier to a widespread use of this technology, however, is its high capital cost, which was in 1980 in the range of US $ 10 to 15 per peak Watt for the generators alone.

Therefore photovoltaic generators are today competitive with other systems only in remote areas, where reliability has a high priority and other energy sources are not available. The main actual applications are for telecommunication, automatic data recording stations, water pumping, solar television, solar refrigeration and electrical power plants. Of these applications, water pumping has the largest potential for extensive use if the prices are coming down.

b) Characteristics and constraints

Since the most important part of the photovoltaic pumping system is the solar cell array, the characteristics of a PV-pump are mainly the same, as of PV-generators in general. However, there are several points to mention especially for the solar pumping application:

- There is another point related to the varying demand of a year: A solar pump has to be sized to be able to satisfy the peak irrigation demand for a given area and these conditions may only last for a relatively short time. At other times, considerable surplus capacity will be available. This is due mainly to variations in crop water demand, changeover between crops, times when no crops are in the field or when rainwater is supplementing irrigation water. The result of this mismatch between power availability and demand is that only part of the available solar energy can be used for irrigation. In other words, these variations lead to an oversizing of the pump. In a typical, but rather good situation, the utilization factor is about 40 %.[1] (see fig. 1) Therefore, with high costs of solar pumps, they can today only be successful in areas where substantial oversizing due to extreme variation in irrigation water demand can be avoided.

Due to the high capital cost of the solar pump, there are at least today and in the immediate future even more serious constraints, limiting its application to fewer areas. As the capital cost (C) is fairly proportional to the installed power capacity, and the power demand is proportional to the product of the total head (H), (height by which the water must be lifted, plus pipe friction and other energy losses), and the maximum flow rate of water (Q), the capital cost is:

$$C = k \cdot H \cdot Q \quad \text{(where k is a constant)}$$

- There is a proportionality between the price of water and the total head, as the price of water is roughly proportional to C/Q. Increasing the head makes solar pumps increasingly uneconomic and also incompetitive with motor pumps. Presently available systems costing over 20$/Wpk can only be economically viable for heads of little more than 1 m.[2] (With a rather high assumption of a 6 US. cents/m3 water cost.)

- The relative capital costs of diesel and gasoline engine pumps are decreasing with increasing power demand, i.e. increasing land area or water demand. On the other hand, the capital cost of photovoltaic pumps is proportional to the installed power capacity. Therefore, solar pumps tend to be more competitive with fuel engine pumps for quite small daily water demands. In the near future, this will be in the range of 15 to 30 m3/day (to suit about 0,3 to 1 ha).[2]

- The above two constraints indicate, that the most potential users of solar pumps in the near future are small farmers living in areas with high groundwater level. These water regimes exist primarily in the large alluvial deltas of Asia, North Africa and Arabia.[3] However, since these people normally possess no capital resources of their own, the capital cost of the solar pumps are a crucial factor in their adoption by farmers.

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1) *Halcrow, W., Small-Scale Solar-Powered Irrigation Pumping Systems, Technical and Economic Review, London 1981*

2) *Halcrow, W., Technical and Economic Review*

3) *Tabors, R.D., The Economics of Water Lifting for Small Scale Irrigation in the Third World: Traditional and Photovoltaic Technologies, MIT, 1979*

The provision of finance to assisst the poorer farmers to meet this first cost is an important aspect of the transfer of the technology. If governments or related national institutions don't take financial actions in this direction, the market for solar photovoltaic irrigation pumping is very restricted.

- It is rather difficult to say something on the social and cultural acceptability of solar pumps, as until now very little experience is available on this aspect. Most actual installations are not representative because they are established in special situations. Obviously, solar pumps are alien elements in rural areas, representing a very high imported technology. The best chance to succeed is given in situations, where irrigation is a familiar technique and a certain industrial infrastructure is already existing. There are a number of barriers to the local manufacture or part-manufacture in developing countries. Particularly, photovoltaic cells need to be manufactured on a rather large scale to bring unit costs down, and developing countries often lack the capability to establish and sustain such an industry.

Several factors lead to the expectation, that capital costs will fall and photovoltaic pumping systems will get more competitive in the future. From these factors, the following will be discussed in the following sections:

- With more experience, design will improve and matching will be optimized, leading to an increased efficiency and reduced required array size.

- Several technical improvements in solar cells and their manufacturing process will make them cheaper.

- Increasing fuel prices will make solar pumps more competitive with conventional motor pumps.

- Economies are resulting from an increasing scale in manufacture and growing markets.

c) Design optimization and matching

The simplest photovoltaic pump consists of a photovoltaic array, a DC-motor and a pump. These elements have to be optimally chosen and matched to each other to give an optimal efficiency. To further increase efficiency in certain applications, electrical control devices and batteries could be used. Today, the optimal achievable efficiency of the total system consisting only of a PV-array, a motor and a pump is about 4,5 %.

This is derived from following (optimal) efficiencies of the individual components:[4]

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4) Halcrow, W., Small-Scale Solar-Powered Irrigation Pumping Systems. Phase I Project Report, London 1981

array cells	11 % at 25° C (10% at operating temperature)
connections	95 %
motor	85 %
pump	55 %
pipework	95 %
total system	4.6 %

However, existing installations mostly have a lower overall efficiency. This is not due, in general, to a wrong calculation of the PV-array size but rather to a poor matching of the characteristics of motor, pump and the generator to the hydraulic requirements.

Another problem are bad pumps, being the weakest part in the whole system. At present array costs, a one per cent marginal increase in pump efficiency (with good pumps in the 40 - 50 % efficiency range) would be worth $ 40 for a 200 W (electrical) system and 80 $ for a 400 W system in array savings.[5] Therefore the choice of a good pump is very important to achieve a decrease of costs.

In the discussion of the criteria for a choice of the elements, only the most promising applications for solar irrigation pumping shall be regarded, i.e. small-scale low-head solar pumping.

For the selection of the pump, the following criteria are most important:

- The pump should have a very good efficiency being at least about 40 - 50 % (under field conditions).

- The pump should be able to establish and maintain prime on the suction side of the pump. In existing applications the loss of prime (e.g. through a cloudy period) is one of the major troubles. The pump should also be capable of running dry without damage.

- In many situations, the pump will be subject to wear from particles suspended in the water. It must be able to pass suspended solids without damage or clogging.

- Another factor are variations in head that might occur in the level of groundwater. With low lift pumping in the 3 - 5 m range, even 1 m variation represents a large percentage of load change. The pump should be able to cope with this without requiring adjustments.

- Low starting torque requirements enable the use of a larger part of the daily solar energy and exclude the need for a battery.

- The characteristics of the pump under varying conditions (head and flow, which can be drawn in a diagram as a current voltage characteristic of the motor-pump), should match well with the optimal power points of the PV-array under varying insolation.

From the large number of available types of pumps, the submerged centrifugal

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5) Halcrow, W.; Technical and Economic Review

pump meets the above requirements best. Other pumps are excluded, because they are not self-priming, have too low efficiencies for low-head applications (positive-displacement pumps) or cannot be matched well to the PV-array characteristic (positive-displacement pumps). The submerged version of the centrifugal pump is preferred, because then no foot-valve is needed.

For proper selection of a pump motor, the following criteria should be observed:

- As for the pump, efficiency is of the utmost importance in minimizing the required solar array size.

- The motor has to serve the needs of the centrifugal pump. Maximum operating speed is between 3000 - 4000 rpm.

- Maintenance and reliability are in remote areas and under tropical environment of major significance.

- The matching of the motor input to the PV-array output should be as simple as possible.

The last point is being best fulfilled by DC-motors, since no DC/AC-converter would be needed. The lower cost of AC-motors is not profitable, because they normally have lower efficiencies than DC-motors in the fractional horsepower range. DC permanent magnet motors are most attractive, as they are more efficient than series or shunt wound DC motors, particularly under part-load conditions. The main maintenance requirement is occasional brush, commutator and bearing replacement. Brushless motors (with the magnets in the rotor and an electronically commutated stator) are available, but in the tropics the electronic circuitry is still too vulnerable and needs good cooling. Compact submersible motor-pump units could prove valuable for solar pump applications.

Obviously optimal matching of the PV-array, DC-motor and centrifugal pump is of utmost importance for PV-array size reduction and predictability of operation.

The pump and motor characteristics can be drawn in different diagrams. For a given head, a centrifugal pump will provide water, if the speed of rotation is greater than a threshold value. With increasing speed, the torque will grow steadily as the water output grows. This situation is represented in fig. 2a.

When the motor and pump are coupled, speed and torque of both motor and pump must be coincident at any given moment. The points of coincidence can be drawn as a curve also in the current-voltage (I/V) diagram of the motor-pump system. Because in the operating range of the DC-motor, current is fairly proportional to torque, and voltage to speed, fig. 2b is very similar to fig. 2a (figures adopted from [6])

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6) Matlin, R.W., *Design Optimization and Performance Characteristics of a PV-Micro-Irrigation System for Use in Developing Countries*, MIT, 1979
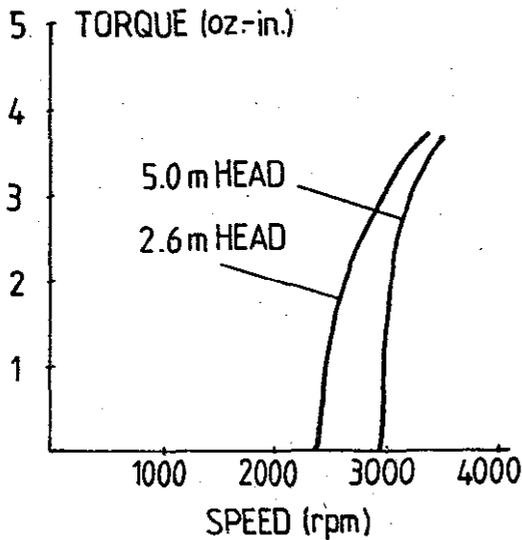
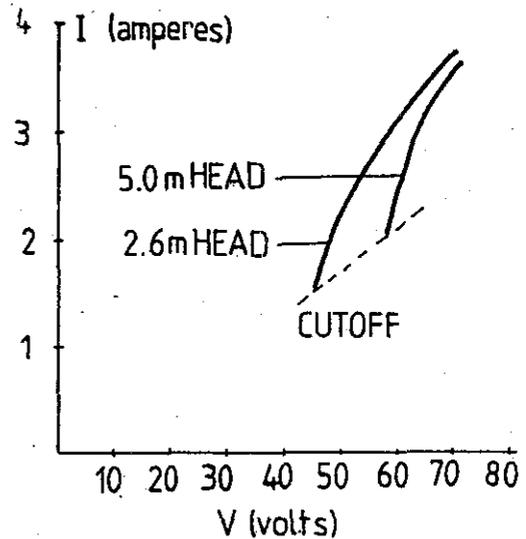Fig. 2a: Torque-speed for centrifugal pump at different heads

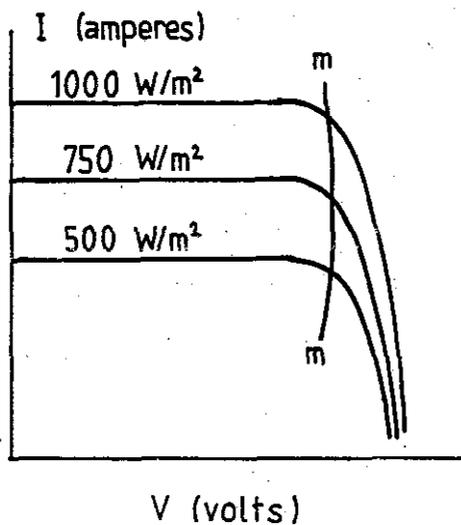Fig. 2b: Current-Voltage for motor-pump system

Fig. 2c: Working curves of PV-array at different irradiance levels
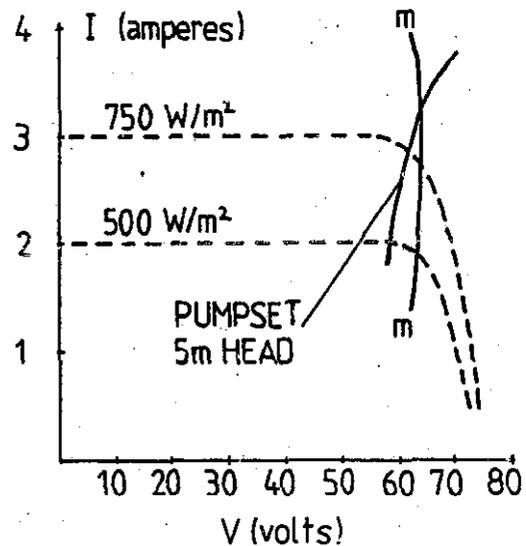
Fig. 2d: Matching of PV-array and motor-pump system

On the other hand, the possible working points of the PV-array at different irradiance levels can also be drawn in an I/V diagram (fig. 2 c). For every irradiance level, one point on the I/V curve signifies maximum power delivery. A curve (m-m) can be drawn through the maximum power points of every irradiance level.

In order to maximize the output of the system under all operating levels of irradiance, the load (I/V curve of motor-pump system at a given head) should coincide as closely as possible to the maximum power curve of the PV-array.

(This can be achieved by connecting the PV-modules in a certain manner, i.e. in
the right relation of parallel connections to in-series connections.) In prac-
tice it is common to match load and array for just one level of irradiance,
such as say 800 W/m2. At lower levels of irradiance, the subsystem power demand
causes the array to operate off the optimum point (fig. 2d).

The correct matching of subsystem and array is a complex analytical process
which is greatly facilitated through the use of a computer model, which permits
an iterative approach to be used.

Two points are worth mentioning:

- For every application a new optimization must be done. This means also,
  that the system is very difficult to optimize, if the water head varies
  or not all relevant factors are known at the time of optimization.

- The system operates only at one irradiance level optimally, while having
  a lower efficiency at all other irradiance levels.

These disadvantages have led to the development of an electronic optimizing
circuitry called maximum power point tracker (MPPT). The MPPT is an automati-
cally controlled DC-DC-converter (or impedance matching device) which changes
the voltage/current ratio (impedance) until the optimal power point of the
array is found.

As the MPPT consumes a certain amount of power (4 - 7 %)[7] the efficiency at
the design point will be lower than without MPPT, but at other irradiance le-
vels it will be better.

Therefore, despite its high price, MPPT's may be profitable in situations where
conditions vary much (irradiance level, array temperatures, pumping head). The
MPPT allows manufacturers to sell standard pumping systems which still function
optimally under significantly different conditions.

Batteries could also be used for power conditioning. But because they require
relatively much maintenance (distilled water), are heavy (movable solar pumps!)
and expensive, their use is not recommended.

To maximize the use of available solar irradiation, tracking of the PV-array
could be considered. Usually the collector is fixed, facing south in the nor-
thern hemisphere or facing north in the southern hemisphere. At noon, the array
surface is normal to the sun's rays, collecting the most possible energy. In
the morning and in the evening, however, less of the available energy is collec-
ted, because the sun's rays don't fall normal on the collector.

If the array is tracked from east to west, almost the full intensity of sun
light (around 1000 W/m2) can be harnessed from the moment when the sun rises to
its setting. Automatic tracking is not suitable in developing countries, as it
complicates the system, increases cost and reduces reliability. But it has been
shown, that through manual tracking at least 40 % extra energy could become

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7) Matlin, R.W., 1979

available.[8] Moving the collector twice per day is only 5 % less efficient than automatic tracking. As this manual tracking is probably necessary only during a short period (month of peak water demand), the array could be sized smaller and the utilization factor increased without much effort and cost.

d) Reducing solar array costs

Solar cells have been known since 25 years, used mainly for spacecraft, and in the past few years are being increasingly used for electricity generation on earth. The basic material for solar cell manufacture is silicon, a material derived from silicon dioxide which is found abundantly in nature as sand.

Silicon is a semiconductor which usually does not conduct electricity, but can do so, if a sufficient amount of light or heat is present. Through the incidence of a photon, an electron can get enough energy to escape from its place in a silicon-atom. An electrical field is necessary, to transport this electron to the surface of the semiconductor and thus to permit a current of electrons to flow through the silicon crystal. This can be achieved, by doping the silicon crystal on both sides with different specific impurities (the result is called pn-junction). For collecting the generated charge-carriers at the surface of the silicon, metallic electrodes are soldered onto the cell. The front side electrode has the form of a grid, to cover as little of the light-absorbing surface as possible.

Most solar cells used in present applications are fabricated from high-purity monocrystalline silicon by the following process: The purified silicon is melted and a perfect crystal is grown drawing a seed crystal slowly from the melt. The silicon crystal is then sawed into thin wafers of about 0.25 mm thickness. A pn-junction is created in each wafer by exposing its surface to a gas of doping material. Finally the electric contacts are attached and the cells are encapsulated with a transparent substance to protect them from air and water.

The described production method yields cells with efficiencies between 10 % and 15 %. The theoretical maximum efficiency of the monocrystalline silicon cell is about 23 %.[9]

The methods to produce solar cells from monocrystalline silicon have been used in the electronic industry since many years. Thus, they cannot be said to be immature. However, the trend for manufacturing electronic components was to pack more and more elements on one chip to reduce the required silicon area. For this reason, the price of silicon doesn't play the same role as in the solar cell application. Certain steps in the manufacturing process could be optimized to reduce solar cell costs. The most expensive steps are the following:

- Very pure monocrystalline starting material is needed to achieve a good efficiency. The reason is, that the charge carriers in the silicon are trapped by impurities and grain boundaries (grains are small crystals with various orientations in a polycrystalline silicon).

8) Halcrow, W., Technical and Economic Review
9) Howell, Y., Adler, D., How Silicon Cells Work, Sunworld, Vol 4/No. 1, 1980

- About 50 % of the expensive starting material is lost during fabrication, mainly through cutting the silicon crystal to wafers.

- The crystal growth and the diffusion process for doping the wafers are very slow.

- The production and fabrication methods are very energy-intensive. The energy payback period of monocrystalline cells is said to be in the range of its lifetime. The solar cell costs will be much dependent on fuel price increases without marked reduction of the energy input.

- Many steps in the production process are not yet automated.

Several methods being developed at the moment, could lead to a cost reduction of the solar cells. They aim at decreasing processing energy requirement, reducing the amount of starting material, automating manufacture etc., while maintaining or even increasing the solar cell efficiency. Among the most promising and most discussed are the following:

- In single-crystal silicon cells manufacture, much of the expensive starting material could be saved, if the cutting of the crystal to wafers could be changed, by drawing a ribbon of crystal silicon from the melt instead of a cylindrical crystal. This technique has been demonstrated in the laboratory and would not only reduce costs but enable automatic (and therefore large-scale) production of solar cells. Ion-implantation of dopants instead of the slow high-temperature diffusion process would reduce energy requirement. Both methods increase damages in the crystal structure (which can partially be repaired) and therefore cause a reduced cell efficiency.

- Attempts have been made to weaken the single-crystal requirement by producing solar cells from thin layers of polycrystalline silicon. Polycrystalline silicon is comprised of many small silicon crystals with various orientations. However, as grain boundaries trap the charge carriers, both, current through the solar cell and efficiency, decrease. This problem is reduced if the grain boundaries are perpendicular to the pn-junction. Today, polycrystalline silicon cells are available (in pilot-scale) with efficiencies around 10 %.

- Crystalline silicon is a rather poor absorber of visible light. Thus, the solar cells should have a thickness of at least 100 micrometers. On the other hand, amorphous silicon (Si-atoms are not ordered in a crystal structure) is a good absorber of visible light so that a thin film of 1 micrometer would be sufficient to absorb the light. Amorphous silicon cells need much less starting material and do not pose the same problems concerning purity and crystallinity as the crystalline solar cells. The manufacturing process is much cheaper, because amorphous silicon is prepared by the condensation of silicon vapour onto a cold substrate. However, the transport of electric charges through the amorphous solid is more difficult, resulting in a poor efficiency of about 5 % in the laboratory today.[10]

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10) for further details, see Adler, D., Amorphous Silicon Solar Cells, Sunworld, Vol. 4/No. 1, 1980

● A fourth possibility for array cost reduction is <u>concentration</u> of the sunlight onto a small spot, which needs less area of solar cell surface. For small-scale applications in developing countries, however, only flat mirrors without tracking mechanism are feasible. This solution will lose its attractivity if cell costs decrease.

In all methods discussed above, reduction of the cell costs below a certain limit is only possible at the expense of a good efficiency. Many cost factors such as land, encapsulation, structure, wiring, installation and transport are strictly proportional to the installed panel area, and therefore inversely proportional to the efficiency of the array. Thus, it is doubtful if solar cells with an efficiency below say 10 % become economic, even if they are very cheap.[11]

e) Economic considerations

Most presently available solar pumping systems are costing more than 30 $/Wpk (prices for delivered systems; one american supplier sells his systems much cheaper). For a typical system of 250 Wpk, CIF-prices would be about 10'000 US $ of which two thirds are solar array costs.

Of course, these prices will decrease, if solar pumping is becoming more attractive. However, the prices cannot fall short of a certain limit. With solar cell costs of zero, the price of the solar array will be at least in the range of 0,5 - 1 $/Wpk. (At 15 % efficiency and a price of 75 - 150 $ per m2 of array area for encapsulation, structure, wiring etc.) In addition to this, about 2 $/Wpk will have to be paid for motor and pump (about 300 $ each for 300 W rated power). Therefore, including transportation and installation, the price of solar pumps will hardly drop below 3 - 5 $/Wpk in the future.

Irrigation is economically viable only if the cost of water can be covered by an increased income from crop production. The economically acceptable price of water depends very much on local variables such as crops and climate, and is economically viable today in the range of 1 - 5 US cents per m3 pumped water. In fig. 3 water prices for different costs of solar pumps are drawn, varying with head.

Two conclusions may be drawn from this figure:

● Today solar irrigation pumping is not economically viable for all heads practically occuring.

● With a price of about 1 US cent/m3 per m pumping head, which corresponds with minimal solar pump costs of 3 - 5 $/Wpk, solar irrigation pumps could become economically viable only for pumping heads below 5 - 6 m.

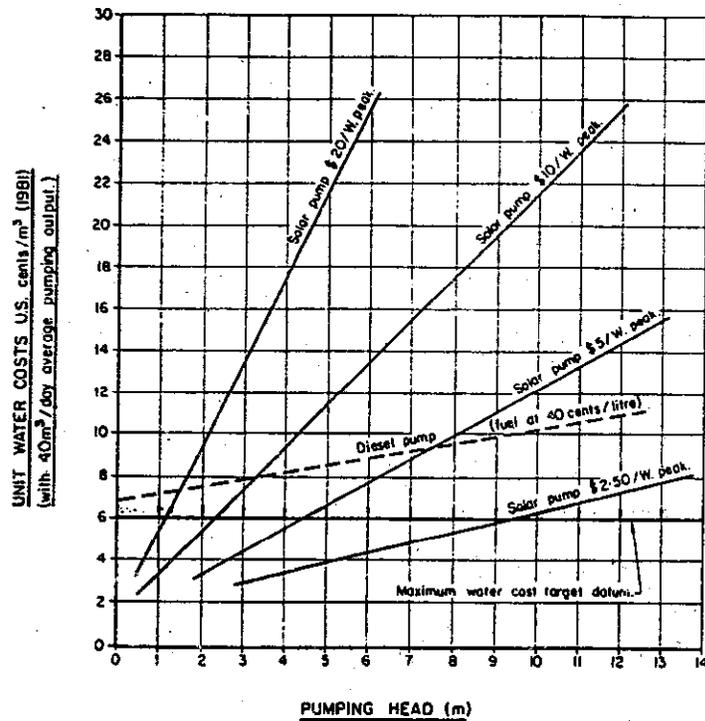11) Durand, H.L., Photovoltaics: Present Status and Future Prospects, <u>Sunworld</u>, Vol 4/No.1, 1980

Fig. 3: Effect of pumping head on water unit costs for a daily output of
40 m3/day Source: Halcrow, W., Technical and Economic Review

In the near future, the solar pump will compete with mainly two groups of pumping systems: conventional motor pumps (diesel, gasoline) and traditional pumps (human and animal powered). This competition depends very much on the power requirement, thus on the area of land to be irrigated.

Today, solar pumps cannot compete with diesel pumps for areas above a quarter ha. However, this situation will change, if array costs decrease and fuel costs increase. Fig. 4 shows the relation between water costs and irrigated area for different fuel prices and solar pump costs. Solar pumps will first become competitive for irrigation of land areas smaller than 1 ha. Later, they could become competitive even for all areas.

For poor farmers on small land holdings, the important question is not, whether the solar pump could compete with diesel pumps, but whether it could compete with traditional pumping methods. Recently, efficient low-cost manual irrigation pumps have been developed. With the Rower Pump for example, two people could pump 40 m3 of water with a 5 m head in 8 hours.[12] This would be enough

12) Rower Pump, Mirpur Agricultural Workshop and Training School, Dacca, Bangladesh (leaflet)
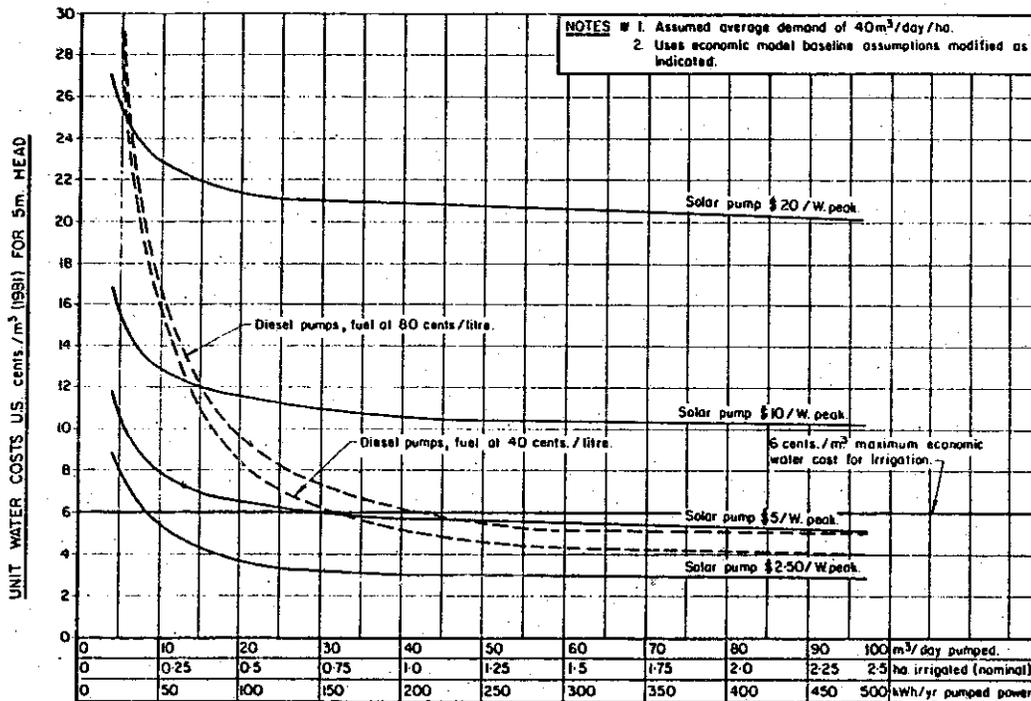
Fig 4: Effects of water demand on water unit costs for 5 m pumping head

Source: Halcrow, W.: Technical and Economic Review

to irrigate an average area of 1 ha. Animal powered irrigation pumping is practised since centuries in many areas of the world. An economical comparision with these techniques is difficult, since it is very dependent on local conditions (fodder, labour costs, bullock rent etc.). However, the following considerations indicate, that solar pumps will hardly be able to compete with traditional methods:

- The attitude of poor farmers towards risk and uncertainty (high discount rate) favours pumping systems with low capital costs. The Rower Pump for example costs about 10 - 13 $, a corresponding solar pump at least 600 $ (with a 3 $/Wpk minimal assumption).

- For the same reason, operating costs (labour, fodder, rent) count less in the farmer's view than capital costs.

- In many rural areas labour and animal power is abundantly available.

The above considerations reflect the point of view of potential buyers and thus represent a financial analysis. An economic analysis (from the point of view of governments), however, could show more benefits for the solar pump.[13] If

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13) *French, D., The Economics of Renewable Energy Systems for Developing Countries, Washington, 1979*

prices of solar pumps decrease enough, governments could take measures to intro-
duce credit mechanisms or subsidies in favour of solar pumps. Unless this is
done, solar irrigation pumps will hardly come into widespread use in the near
future.

f) Conclusions

Solar pumps are today not economically viable for irrigation purposes. Neverthe-
less, the market for solar photovoltaics will grow as there are other economi-
cally viable applications in remote areas, where reliability is very important.
Pumping of drinking water for instance belongs to this group of applications.
The growing market and technological improvements will lead to decreasing solar
cell prices. With increasing fuel costs, solar pumps will become competitive
with motor pumps at least for small land holdings (but only for low pumping
heads).

Small farmers with little purchasing power will hardly be in a position to af-
ford solar pumps, even if the solar cell costs decrease dramatically. As is the
case with many other technologies, financing mechanisms will have to be devised
and substantial subsidies will be required to make a new technology accessible
to the small and the very small farmer, who constitute the majority of the
rural population in the developing world.

g) Suggested further reading:

French, D., The Economics of Renewable Energy Systems for Developing Countries, Washington D.C., 1979

Halcrow, W., ITDG, Testing and Demonstration of Small-Scale Solar-Powered Pumping Systems, State of the Art Report, UNDP/World Bank, London, December 1979

Halcrow, W., ITDG, Small-Scale Solar-Powered Irrigation Pumping Systems, Phase I Project Report, UNDP/World Bank, London, July 1981

Halcrow, W., ITDG, Small Scale Solar-Powered Irrigation Pumping Systems, Technical and Economic Review, UNDP/World Bank, London, September 1981

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Matlin, R.W., Design Optimization and Performance Characteristics of a Photovoltaic Micro-Irrigation System for Use in Developing Countries, MIT Lincoln Laboratory, Lexington, 1979

Saunier, G., Folea, D., Electrical Solar Energy Applications in Remote Rural Area, Proc. of the Regional Asia and Pacific Workshop on the Applications of Solar Energy in Agricultural and Post Harvest Activities, Bandung, 12 - 15 Jan. 1981

Smith, D.V., Photovoltaics in the Third World, MIT, Massachusetts, 1979

Tabors, R.D., The Economics of Water Lifting for Small-Scale Irrigation in the Third World: Traditional and Photovoltaic Technologies, MIT, Massachusetts, 1979

h) Suppliers of photovoltaic pumps (not complete)

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95102 Argenteuil
France

Pompes Guinard
179, Boulevard Saint-Denis
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